Effectiveness of different flexibility options and innovative network technologies for the use in the BDEW traffic light concept, on the basis of a German distribution grid

T. Ackermann*, E. Tröster, L. Hülsmann, Energynautics GmbH Germany
U. Ohl, M. Koch, EWR Netz GmbH Germany

Summary

The continuous expansion of distributed generation (DG), mainly rooftop and free-field photovoltaic (PV) systems as well as wind power plants, is changing the power flow landscape in the distribution grid: During times of high solar irradiation and wind speeds, generation can exceed load on a distribution feeder by a multiple. This pushes cables and transformers to their thermal limits and may lead to voltage deviations outside of the allowed +/-10 % of nominal value. Furthermore, new electrical consumers, such as electric vehicles and heat pumps, may also aggravate the network during peak demand times. However, these situations occur only during few times of the year which makes traditional grid reinforcements an expensive countermeasure. Instead, shifting demand from times of high load to times of high PV and wind power generation can offer cheaper alternatives to mitigate grid congestion and delay or prevent grid reinforcements. In light of this, the German Association of Energy and Water Industries (BDEW) has developed the “BDEW smart grid traffic light” concept. Its aim is to communicate regional flexibility needs during the amber phase by means of a local flexibility market in order to stay in the green phase, as opposed to the red phase where a grid congestion prevails. DESIGNETZ, one of five showcases of the German funding program “Smart Energy Showcases - Digital Agenda for the Energy Transition” (SINTEG), is intended to demonstrate the working principles of such a flexibility market. This paper deals with the simulation results of the traffic light concept. For this, a radial medium voltage (MV) feeder in a rural area is analysed, supplying multiple small villages. The feeder is heavily penetrated by PV generation but still only 22% of suitable rooftop area is occupied by PV. The PV generation has been further increased and, additionally, new electric vehicles and heat pumps were modelled, to represent a scenario of the feeder in the year 2030. Load flow calculations in DIgSILENT PowerFactory show that this leads to voltage violations outside the defined ranges. Three flexibility options, namely shift in electric vehicle and heat pump demand as well as PV curtailment, are utilized in the traffic light concept and chosen based on their sensitivity to alleviate the grid congestion as well as their costs. The simulation results show that the concept can effectively allocate the most cost- effective flexibility options and keep the MV feeder within its safe operation boundaries. This lowers PV curtailment by 15 % for the analysed grid and reduces costs by 6 % compared to the case where only PV curtailment is applied. The cost benefits of such a concept need however be weighed against the communicational and regulatory challenges that such a flexibility market poses.

1. Introduction

With increasing capacities of distributed renewable generation, such as photovoltaics (PV), being connected to the distribution networks, distribution system operators (DSOs) are facing a number of challenges. In grids that were designed for unidirectional flows from the transmission grid to the end customers, high shares of distributed generation can lead to voltage and overloading problems (grid congestion). Voltages have to be kept within a +/-10 % band of the rated voltage [1], while cables and transformers need to stay within their thermal rating. Congestion in the distribution grids may be aggravated

* t.ackermann@energynautics.com

KEYWORDS
Grid congestion - Overvoltage - Distribution grid - Flexibility market - Demand side management - Electric vehicles - Heat pumps - Traffic light - BDEW

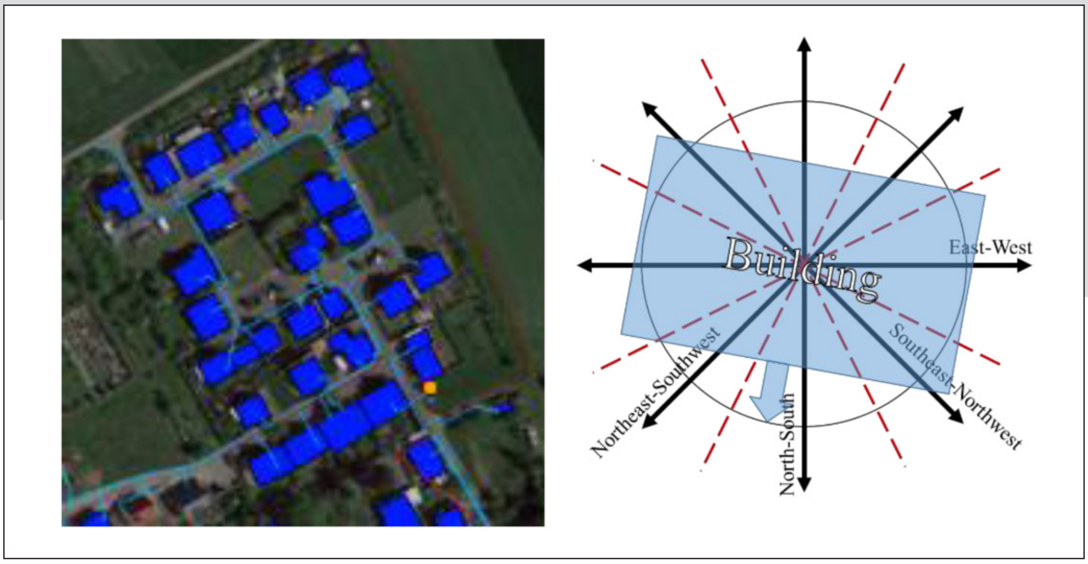

Figure 1: Analysis of rooftop PV potential by GIS data analysis (top) and categorization according to orientation (bottom)

further by increasing numbers of heat pumps and electric vehicles (EV) that increase electricity consumption. New control strategies are thus necessary to alleviate local grid congestion problems. Demand side management (DSM) can be used to shift heat pump operation and EV charging from times of high demand to times of low demand or excess PV and wind power generation, increasing the hosting capacity of a grid for both renewables and new demand.

Providing this flexibility at the right location and at the right time requires both IT infrastructure that enables the necessary communication, and a defined regulatory framework governing all market participants to work effectively towards the three general energy policy goals: Security of supply, affordability and sustainability.

In this sense, the German Association of Energy and Water Industries (BDEW) has proposed the BDEW traffic light system. It enables DSOs to signal a local flexibility market if a grid congestion problem prevails. Subsequently, the amount of necessary flexibility is determined in a specific grid segment. Flexibility providers and aggregators then compete against each other and the most cost-effective providers are chosen.

This paper is part of the DESIGNETZ project [2], one of five showcases under the German funding program “Smart Energy Showcases – Digital Agenda for the Energy Transition” (SINTEG). It seeks to test the BDEW traffic light mechanisms through simulations on a model of a real distribution network described in Chapter 2. The BDEW traffic light system is explained in more detail in Chapter 3, followed by a description of the modelled flexibility options, namely heat pumps, EVs and PV curtailment. Finally, simulation results are presented in Chapter 5 and a conclusion given in Chapter 6.

In subsequent project phases the BDEW traffic light system will be put into real-life practice and tested for its practicability and effectiveness.

2. Model setup

2.1. Distribution feeder model

To study the effects of demand and generation flexibility embedded in a flexibility market framework, steady-state load flow calculations are performed with DIgSILENT PowerFactory on a 20 kV distribution feeder located close to Worms, Germany. Only the MV network is modelled, no LV grids are considered. Loads are predominantly households, modelled with standard load profiles, and aggregated through a total of 49 MV/LV substations. Line types consist mostly NA2XS2Y 3x1x150 cable types and Al_St_95 overhead line types. The feeder has a length of about 22 km, with a large 7.3 MWpeak (MWp) PV power plant located at a distance of 17.5 km from the primary substation and only short side-branches. Together with an installed PV capacity of 4.4 MWp in the LV grids, this is already leading today to large voltage deviations of around 0.05 p.u. along the MV feeder, hence allowing only a small voltage band for the LV grids in order not to violate the EN50160 threshold of 1.10 p.u. Additional rooftop PV generation as well as new heat pump and electric vehicle demand are added, to represent shares expected for the year 2030. They are described hereinafter.

2.2. PV development

Only rooftop PV potential is considered and no new ground-mounted PV power plants were added. Rooftop PV potential was estimated using OpenStreetMap building and residential area data [3]. No building data was available for some substations and an approximation based on the residential area was used. The orientation of each building was evaluated, by considering the longest side of the building to be the dominant factor to determine its roof’s orientation. Only south oriented buildings, as shown in Figure 1 were considered suitable for PV installations and only 50 % of the building area could be used for PV systems. Approximately 60 % of all buildings in the area were facing south. This led to a potential for PV rooftop installations of 20 MWp, with 4.4 MWp rooftop PV already installed along the feeder. The installed rooftop PV power was then increased by adding PV plants at each substation until one of the following thresholds of the total PV potential was reached at the substation: 30 %, 50 %, 70 %. Anything above 70 % of total PV potential was not increased. This results in a 68% increase in rooftop PV capacity in 2030, corresponding to

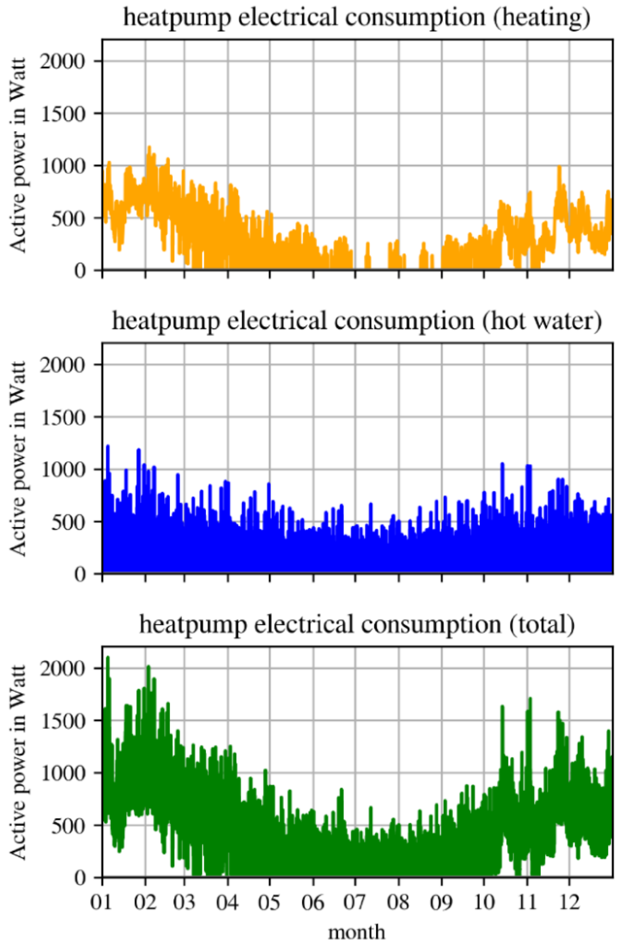

Figure 2: Electrical demand of the heat pump for heating, hot water and in total

2.3. Heat pump model

For 2030, a heat pump penetration rate of 11.9 % according to [4] is assumed. Heat pumps were modelled with an aggregated profile of 40 heat pumps. This is roughly the average number of heat pumps per village connected to the feeder in 2030. Measured solar irradiation and temperature values for the entire year 2015 in hourly resolution, obtained from PVGIS [5], were used as inputs for heating demand. Heating demand was disabled if outside temperatures exceeded 15 °C. To determine hot water energy demand, the CREST demand model [6], a high-resolution stochastic model of domestic thermal and electricity demand, was used. The combined heating and hot water energy demand, in a 15-minute resolution for a whole year, was then scaled to the number of heat pumps.

Based on both heat demands for heating and hot water, the total electricity consumption of the heat pumps can be obtained according to (1).

$$P_{el} = \frac{Q}{COP} = 0.0008 \cdot \left(T_{ft} - T_o\right)^2 - 0.138 \cdot \left(T_{ft} - T_o\right) + 7.4545 \tag{1}$$

Q: Heating and hot water demand
COP: Coefficient of performance of the heat pump
T_{ft}: Flow temperature (heating 40 °C, hot water 60 °C)
T_o: Outside temperature

Normalizing the aggregated profile of 40 heat pumps to a single heat pump results in the profile shown in Figure 2. It can be observed, that due to the aggregation, the maximum value of the averaged electrical consumption of the single heat pump is lower compared to the maximum capability of typical heat pumps (e.g. 3 kWel). Further, a seasonal trend can be observed in the total consumption, which results from the significantly lowered electrical demand for heating during summer as well as higher outside temperatures that improve the COP of the heat pump. The electrical demand for providing hot water is also slightly lower in summer, mainly caused by higher outside temperatures.

2.4. EV model

The EV modelling is based on a large-scale German mobility study [7]. In this study, data has been collected on trip numbers depending on weekday, time and activity as well as driving duration. Based on these, probability distributions are set up and a one-year driving profile is randomly created for each EV, specifying departure and arrival times as well as driving distance.

The driving profiles are then translated into a charging pattern with the assumptions as seen in Table I. It is assumed that the EV is recharged only if the SOC at EV arrival has fallen below 50 % or if one of the next two trips will fully deplete the battery, assuming perfect foresight of the EV user's upcoming travels. Charging the EV as soon as it returns, keeps the average SOC high, which has detrimental effects on battery lifetime [8], [9]. Additionally, this charging strategy has only negligible impacts on user comfort, as the number of times with full battery depletion during the trip increases only from 0.91 % to 0.94 %. However, it enables the EV to be charged also during times when a grid congestion due to excess generation exists and may therefore offer an additional income source for the EV user. Figure 3 shows a typical charging profile during one summer week, as opposed to the daily normalized PV output of a 1 kWp PV plant.

Indicator	Assumption
Battery capacity	60 kWh
Fuel economy	20 kWh/100 km
Driving range	300 km
Charging power at home	11 kVA
Charging efficiency	98 %
Power factor	0.98 var consuming
EV share of total cars	7.6 %
Number of EVs	346

Table I: Assumptions on the electric vehicle parameters

3. Description of BDEW traffic light concept

3.1. Definition of green, amber and red phase

In two papers [10], [11] from 2015 and 2017, the German Association for Energy and Water Industries (BDEW) has proposed the BDEW traffic light concept. The idea behind this concept is that a three step system indicating the state of grid congestion is established for distribution grids. In this regard, the green phase signalizes that no grid congestion exists and the DSO is able to keep voltage and loading limits within safe boundaries by his own means, such as voltage control with tap changers or reactive power control. During the red phase, on the contrary, the DSO must intervene by curtailing active power (load or generation, depending on the nature of the problem) to stay within the defined limits. Unrestricted electricity trading is interrupted. In between the two an amber phase is defined, where a potential bottleneck is predicted in a defined network segment. In this phase, the DSO calls upon flexibility that is offered by market participants, to prevent the red phase and allow a more economical cost-allocation of flexibilities.

	GREEN	AMBER	RED
Current I_{max}	0 % to 80 %	80 % to 100 %	> 100 %
Voltage $U_{min/max}$	+/- 4 %	-5 % to -4 % +4 % to +5 %	< -5 % > 5 %

Table II: Permissible voltage and current limits for each traffic light phase

In this project, the traffic light concept has been put into practice on the specific described distribution feeder to quantify its effect and test its ease of use. During the project, a real-life example of this traffic light concept is planned to be set up. To allow for a voltage deviation of up to 0.05 p.u. in the LV grid, an applied design criteria of

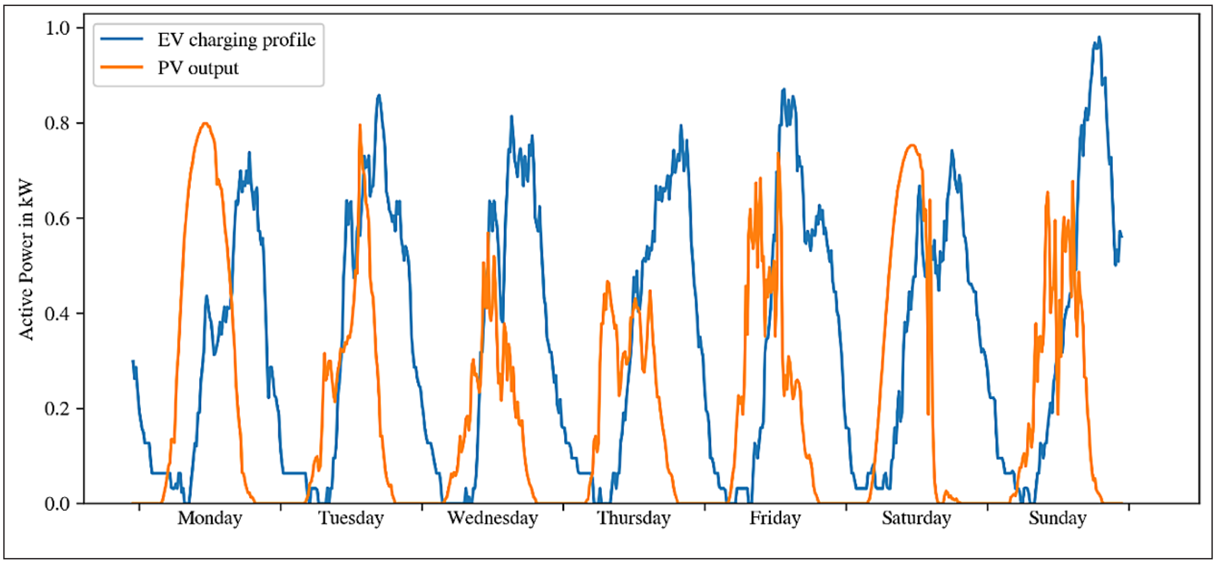

Figure 3: Normalized EV charging profile per EV in blue, normalized PV profile per kWp PV output in orange, both for a summer week

the local DSO, a maximum voltage band of +/-5 % has to be kept within the MV feeder. The green phase is defined as being within 80 % of the permissible voltage and overloading limits, while the red phase is evoked if the permissible thresholds are exceeded. This sets the criteria for the different traffic light phases according to Table II. With a better knowledge of voltages in the MV and LV networks, e.g. by means of a wide area voltage control, these limits can be expanded, reducing the need for flexibility. As can be seen in Figure 4, in the 2030 scenario upper voltage limits are consistently violated during day times in summer. This results also into loadings above 80 % but not exceeding 100 %. No undervoltage violations are observed as the penetration of EVs and heat pumps is too low to cause any problems.

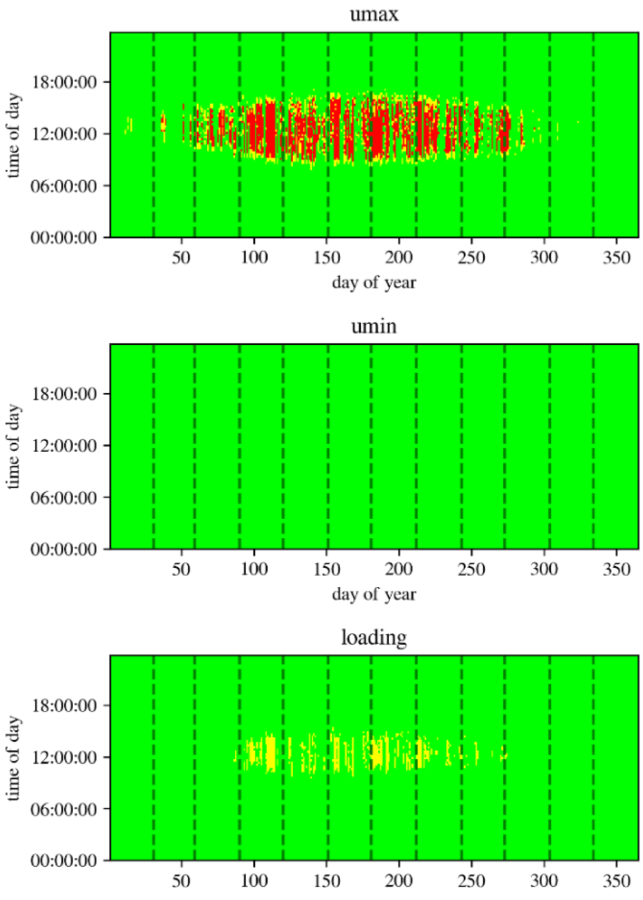

Figure 4: Categorization of maximum and minimum voltage as well as loading into green, amber and red phase of the BDEW traffic light system for the 2030 scenario

3.2. Flexibility list

The flexibility list is one of two mechanisms described in [11] to put a flexibility market into practice. The flexibility list describes within which boundaries, or flexibility bands, the active power output of all flexible users (here heat pumps, EVs, and PV) has to operate. Hereby, it specifies the maximum feed-in (Pmin) and demand (Pmax) that limits the combined output power of all flexibility providers, adjusted by their respective sensitivity, to keep within the allowed voltage and overloading (current) limits. An example is shown in Table III.

The voltage sensitivity, shown in Figure 5, is based on the resistance between the HV/MV substation and every MV/LV substation. Therefore, it shows the effect on the voltage for each flexibility option connected to the substations. That is, if a flexibility option at the end of the feeder (substation 29, see Figure 5) cannot be activated, roughly triple the amount must be activated at substation 11 to gain the same effect on voltage. Only the effect on the main branch of the feeder was assessed, allowing side branches (substation 30 – substation 48) to be aggregated with respect to the main branch. This is a reasonable simplification as voltage problems do not occur on the side branches due to the large PV plant connected to substation 22 highly influencing the voltage. However, long side branches with large consumption or generation would necessitate a further split up of the flexibility list for the different network sections.

The current sensitivity describes the impact of each option on the thermal bottleneck in the network, i.e. the element that receives the highest loading. The location of the bottleneck may change depending on the feed-in and loading situation, and even multiple bottlenecks may have to be considered. In the analyzed network, the location is typically between substation 02 and 03, as the cable sections before substation 02 have larger cross-sections. Hence, all substation except number 01 and 02 have a current sensitivity of close to 1, deviating from unity only due to additional line losses. These line losses can negatively affect the line loading in the case of loads (sensitivity > 1) or positively it in the case of generation (sensitivity < 1).

To give an example: 1 MW of feed-in power at the end of the feeder (substation 29) reduces the voltage flexibility band by 1 MW (sensitivity = 1), while it reduces the current flexibility band by only 0.890 MW as line losses between substation 03 and 29 have to be taken into account.

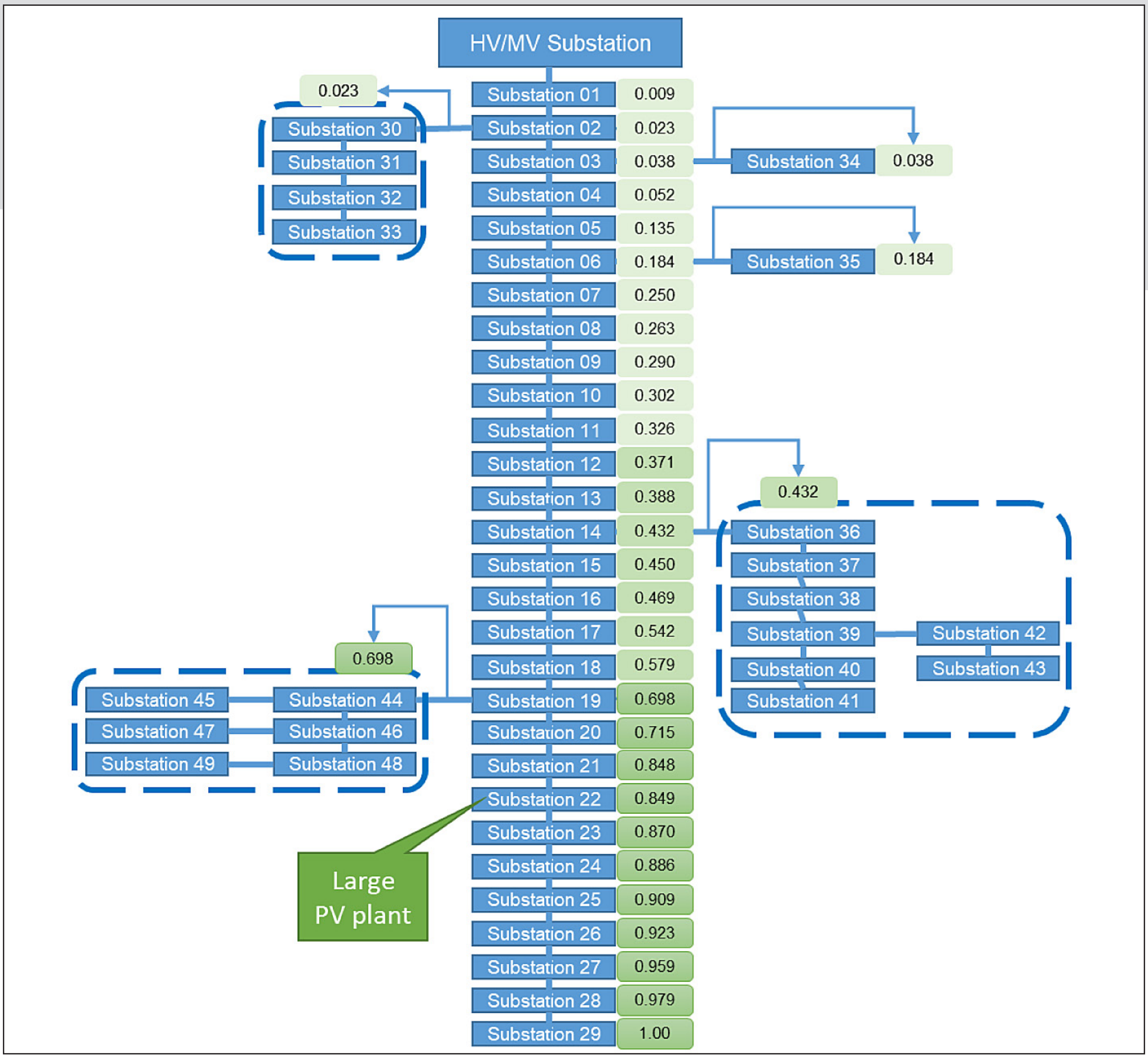

Figure 5: Determination of voltage sensitivities for each substation

Likewise, 1 MW of feed-in power at substation 03 would result in a reduction of only 0.038 MW for the voltage flexibility band but 1 MW for the current flexibility band.

Flexibility list		
Grid operator	**Grid segment**	**Time**
EWR Netz GmbH	MV grid ID 1234567	06.07.2018 12:00 – 12:15
Flexibility band	**Voltage violations**	**Current violations**
	Pmin = -5.52MW (cons) Pmax = 3.92MW (gen)	Pmin = -10.09 MW (cons) Pmax = 7.14 MW (gen)
ID	**Voltage sensitivity**	**Current sensitivity**
HPs @ substation 01	0.009	0
EVs @ substation 01	0.009	0
PVs @ substation 01	0.009	0
HPs @ substation 02	0.023	0
EVs @ substation 02	0.023	0
PVs @ substation 02	0.023	0
HPs @ substation 03	0.038	1
EVs @ substation 03	0.038	1
PVs @ substation 03	0.038	1
…	…	…
HPs @ substation 29	1	1.123
EVs @ substation 29	1	1.123
PVs @ substation 29	1	0.890
…	…	…
HPs @ substation 48	0.698	1.099
EVs @ substation 48	0.698	1.099
PVs @ substation 48	0.698	0.910
HPs @ substation 49	0.698	1.099
EVs @ substation 49	0.698	1.099
PVs @ substation 49	0.698	0.910

Table III: Flexibility list for the analysed distribution grid with flexibility band and sensitivities of flexibility providers. Pmin specifies the flexibility band for demand, Pmax for generation.

4. Flexibility control and activation

In the considered network, only problems due to feed-in of PV plants occur. The penetration of heat pumps and EVs is too low to cause any problems during high demand. Therefore, only flexibility measures to alleviate excess generation are described. The flexibilities are activated based on their cost as well as their sensitivity to reduce the overvoltage or overloading problem. The costs have been chosen according to Table IV. Costs for PV curtailment have been obtained based on their feed-in tariff. For heat pumps and electric vehicles no such data is available and have been chosen arbitrarily to show the principles of operation with a flexibility list. With the assumed flexibility costs, an electric vehicle with a sensitivity of 1 will be activated before a heat pump with sensitivity of 0.3.

For each time step, flexibility measures will be activated as long as the flexibility band (see Chapter 3.2) is violated, starting with the cheapest flexibility measure.

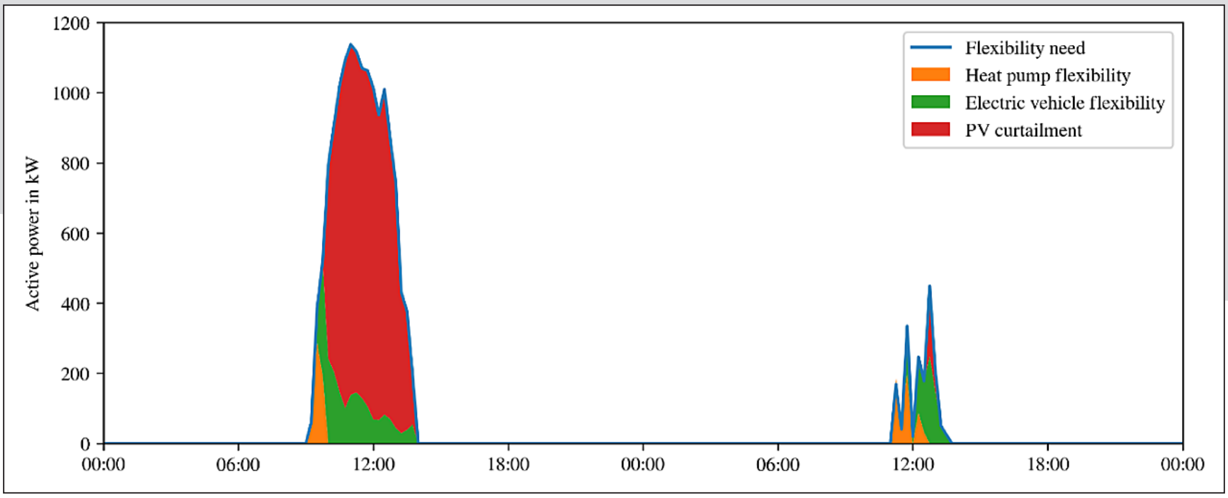

Figure 6: Flexibility activation of heat pumps, electric vehicles and PV curtailment for two days in March

Flexibility measure	Price
Heat pumps	0.025 €/kWh
Electric vehicles	0.050 €/kWh
MV PV curtailment	0.106 €/kWh
LV PV curtailment	0.122 €/kWh

Table IV: Costs for flexibility provision

4.1. Heat pump flexibility

A 200-litre storage tank for the heating system was assumed for every heat pump. The temperature of the storage can be raised by up to 10 °C, providing a certain flexibility to increase the electrical consumption of the heat pump. This temperature difference is provided by an increased output of the 3 kWel heat pump. If the time for flexibility provision has passed, the temperature is gradually lowered again by the heating and hot water demand of the household.

4.2. Electric vehicle flexibility

During normal operation EVs at home are only charged if their SOC falls below 50 %. To provide flexibility for congestion problems, also available EVs with SOCs above 50 % can be charged. To prevent frequent charging interruptions due to changes in the grid state, the charging process is not interrupted until the SOC has reached again 100 % or the car is departing.

4.3. PV flexibility (curtailment)

As a last option, PV generation is curtailed. Curtailment has been assumed to be about 2 and 4 times more expensive than heat pumps and EVs, respectively. However, PV curtailment with a sensitivity of close to 1 will still be chosen over heat pump and EV activation with a sensitivity of e.g. 0.1. Also, the provided flexibility by heat pumps and EVs is limited, and curtailment can be unavoidable in some situations. However, the flexibility list ensures that the most cost-effective options are selected.

5. Simulation results

Following the price list as provided in Table IV, most heat pump flexibility is provided first, followed by the electric vehicle flexibility, and using PV curtailment as the least preferred option. Figure 6 shows the amount of flexibility needed and how the different flexibility options serve this flexibility over time. As can be seen, heat pump flexibility is activated first but has only a small overall capability of taking up excess generation. Subsequently, electric vehicles are activated next. As the charging process may take up to a few hours, the uptake of excess energy is spread out over time. Additionally, new EVs are returning home and offer additional flexibility at later time points. Nevertheless, a large part of excess generation needs to be curtailed on the first day, as heat pump and EV flexibility is not high enough. On the second exemplary day, less flexibility is needed. Hence, curtailment can be reduced to nearly zero.

As a result, the voltage is reduced below its threshold of 1.04 p.u. The deviation from the 1.04 p.u. can be

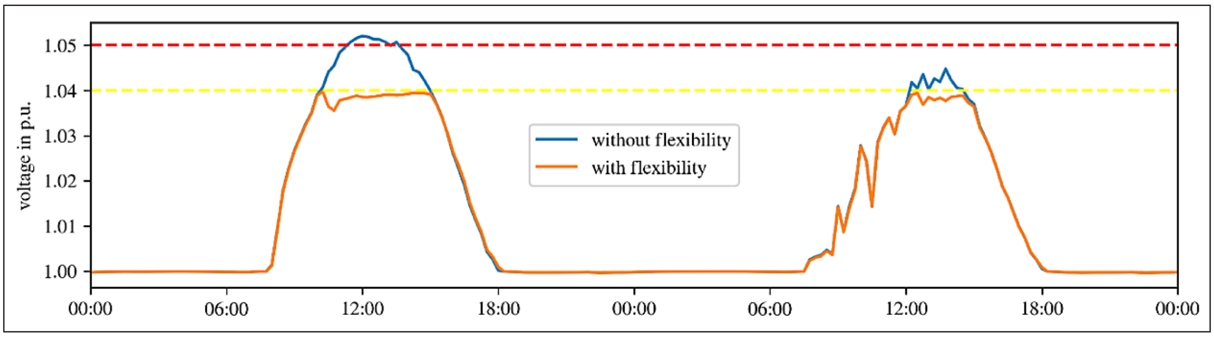

Figure 7: Voltage profile with and without flexibility provided for two days in March

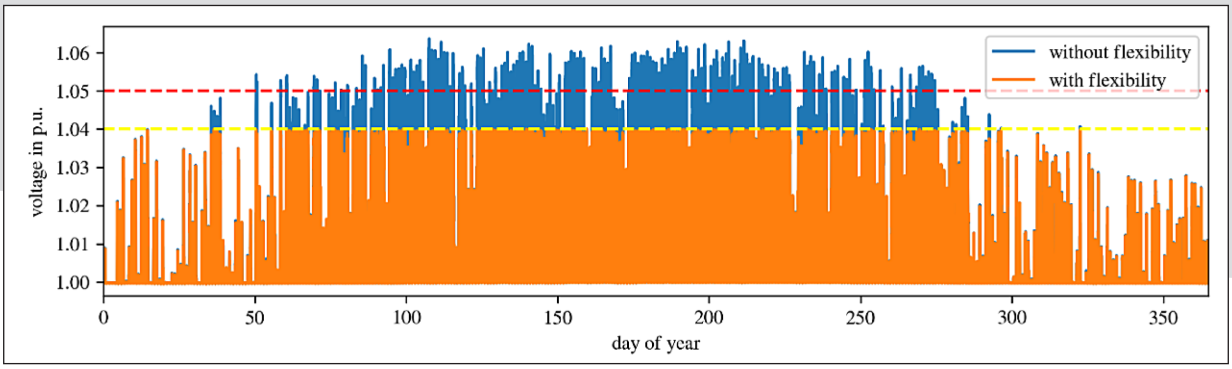

Figure 8: Voltage profile with and without flexibility provided for the entire year

attributed to changes in reactive power and the change of voltage sensitivity due to different loading and voltage levels. Figure 8 shows that the voltage threshold is kept throughout the whole year.

Table V shows the overall contribution of the different flexibility options towards the overvoltage reduction for one year. With heat pump shares of 11.9 % and EV shares of 7.6 %, curtailment can be reduced by 15 % while costs can be reduced by 6 % with the cost assumptions in Table IV. Furthermore, most curtailment is provided by the large PV plant as it is located towards the end of the feeder and can be curtailed for a cheaper price than LV connected PV plants. The necessary PV curtailment is below 0.04 % for any PV plant in both cases.

6. Conclusion and discussion

The paper shows a concept how different flexibility options can be integrated into a single framework, to select the most cost-effective option to mitigate local grid congestion problems (voltage violations and overloading). The framework is called the BDEW traffic light system, proposed by the German Association of Energy and Water Industries (BDEW). The concept is applied to a medium voltage feeder for the year 2030, with high PV penetration and new flexible demand, namely heat pumps and electric vehicles. To provide flexibility, heating demand and EV charging can be delayed as well as PV active power output curtailed. Based on the cost of providing flexibility and the sensitivity that the respective flexibility has on the grid congestion problem, the least expensive options are chosen. As a result, voltage levels are consistently kept under the defined threshold of 1.04 p.u. Further, PV curtailment is reduced by 15 % and costs by 6 % compared to the case where only PV curtailment is applied.

The concept is not limited to the flexibilities integrated here. Any other flexibilities, such as batteries or combined heat and power units, can be added to participate in this flexibility market. With a gradual increase of generation and new loads, the costs for flexibility will increase, up to the point where grid extension or other options offer cheaper alternatives to the DSO. Hence, such upgrades are effectively delayed or in some cases fully prevented.

To facilitate the BDEW traffic light concept, a high degree of coordination is needed, e.g. by means of smart meters. The flexibility list including the sensitivity matrix can change based on the demand/generation situation and the network topology, which needs to be continuously

Flexibility option	**Contribution to flexibility band**	**Active power needed**	**Average sensitivity**	**Costs**
With heat pumps and electric vehicles				
Heat pumps	27 MWh (3.9%)	47 MWh	0.57	1182 €
Electric vehicles	74 MWh (10.7%)	117 MWh	0.63	5840 €
MV PV curtailment	514 MWh (74.4%)	605 MWh	0.85	64162 €
LV PV curtailment	76 MWh (11.1%)	77 MWh	0.99	9423 €
Total	691 MWh	846 MWh		80607 €
Without heat pumps and electric vehicles (only curtailment)				
MV PV curtailment	602 MWh (87.0%)	708 MWh	0.85	75020 €
LV PV curtailment	89 MWh (13.0%)	90 MWh	0.99	10987 €
Total	691 MWh	798 MWh		86007 €

Table V: Resulting contribution and costs of the different flexibility technologies for one year communicated with the flexibility providers as well as the contracted flexibility.

Furthermore, it should be noted that enough flexibility liquidity needs to be available to ensure operability and competitiveness. Lastly, the activation of flexibility should not result in violations in the lower voltage levels. Hence, it is foreseen that the BDEW traffic light will encompass all voltage levels in the future.

7. Bibliography

[1] *EN 50160, "Voltage characteristics of public distribution systems," 2010.*

[2] *"DESIGNETZ." [Online]. Available: https://[Accessed: 26-Mar-2018]. [3] OpenStreetMap contributors, "Planet dump retrieved from https://planet.osm.org." 2018.*

[4] *M. Koch et al., "BWP-Branchenstudie 2015," p. 44, 2015.*

[5] *Joint Research Centre, "Photovoltaic geographical information system," 2018. [Online]. Available: . [Accessed: 26-Mar-2018].*

[6] *E. McKenna and M. Thomson, "High-resolution stochastic integrated thermal-electrical domestic demand model," Appl. Energy, vol. 165, pp. 445–461, 2016.*

[7] *R. Follmer, B. Lenz, B. Jesske, and S. Quandt, "Mobilität in Deutschland 2008," Tempo, p. 214, 2008.*

[8] *B. Lunz, H. Walz, and D. U. Sauer, "Optimizing vehicle-to-grid charging strategies using genetic algorithms under the consideration of battery aging," 2011 IEEE Veh. Power Propuls. Conf. VPPC 2011, 2011.*

[9] *G. Lacey, T. Jiang, G. Putrus, and R. Kotter, "The effect of cycling on the state of health of the electric vehicle battery," Proc. Univ. Power Eng. Conf., 2013.*

[10] *BDEW German Association of Energy and Water Industries, "Smart Grid Traffic Light Concept," no. March, 2015.*

[11] *BDEW, "Konkretisierung des Ampelkonzepts im Verteilungsnetz," 2017.*